# A Next Generation Net Primary Production Model for Application to MODIS Aqua


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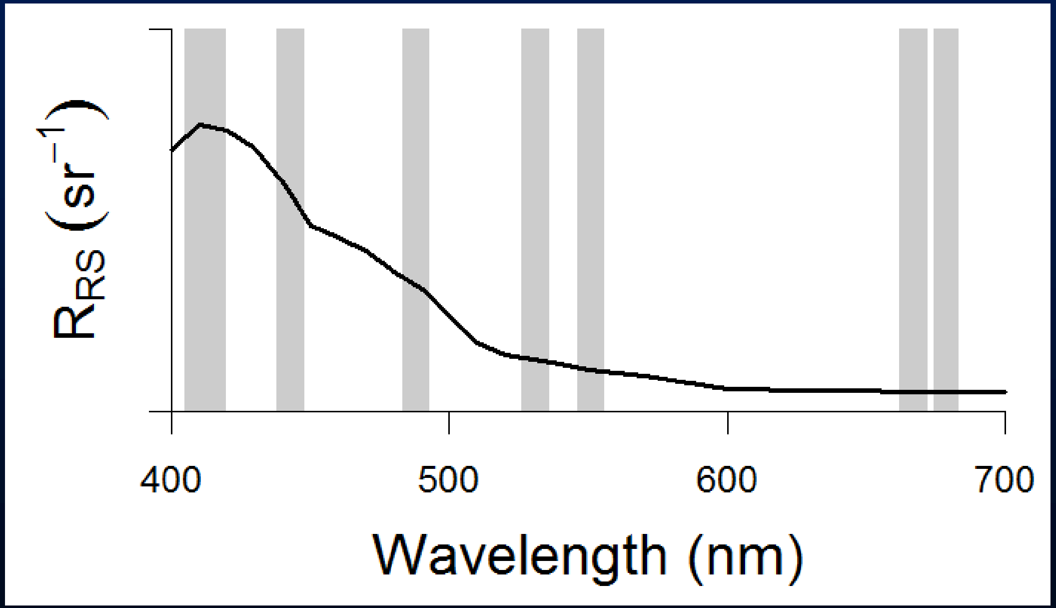
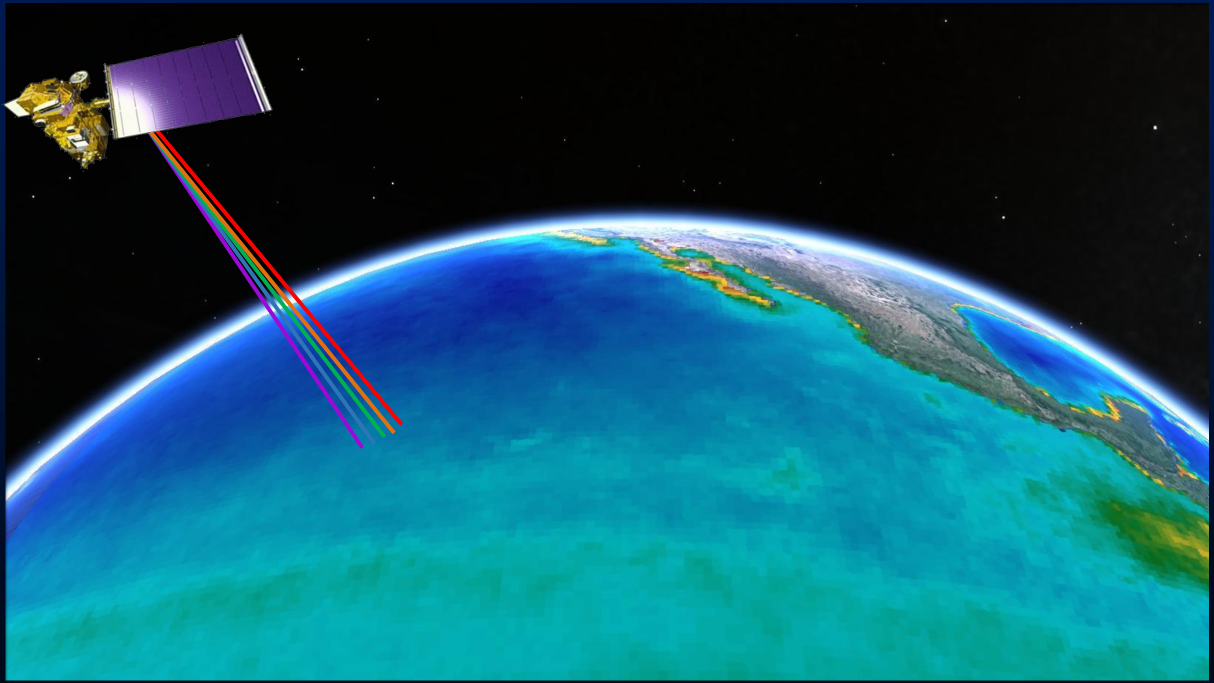
# Ocean Color Remote Sensing: Science & Challenges

Ocean Color $(R_{RS}(\lambda))$ → Net Phytoplantkon Production (NPP)

Growth Rates (μ)



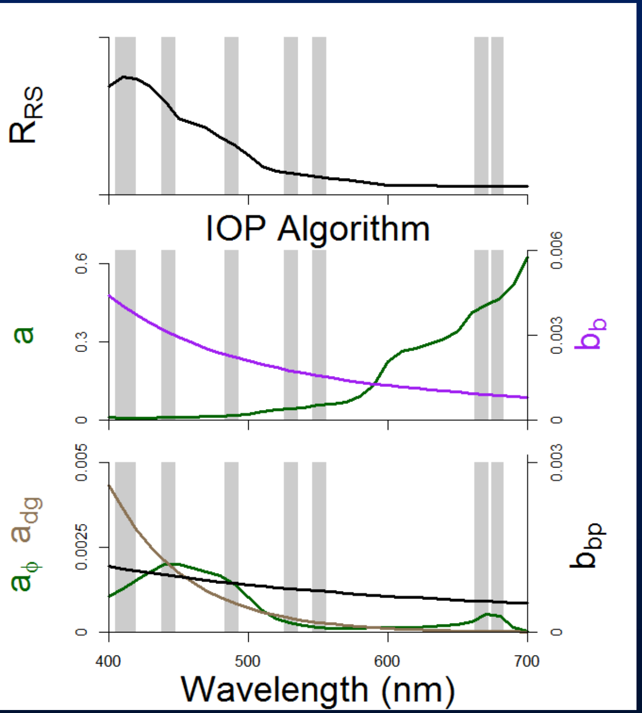



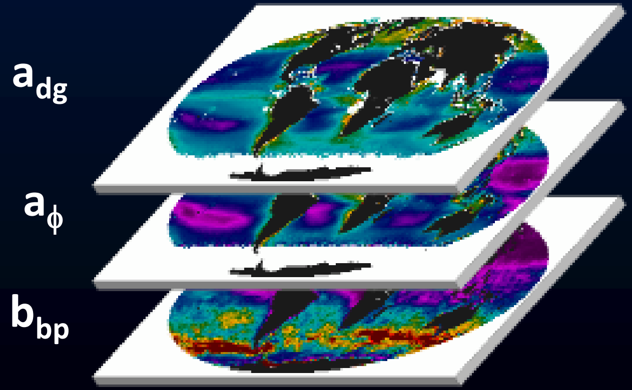
# NPP Models

$$R_{RS}(\lambda) \sim \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$$

- Spectral inversion algorithms now permit retrievals of Inherent Optical Properties (IOPs) from space (Lee et al. 2002; Maritorena et al. 2002; Werdell et al. 2013).

- The Carbon, Absorption, Fluorescence and Euphotic-Resolved (CAFE) model framework seeks to incorporate these products into a mechanistic model of NPP and μ.




Westberry, T.K. and M.J. Behrenfeld. 2014. Oceanic Net Primary Production. In: *Biophysical Applications of Satellite Remote Sensing*. [ed.] J. Hanes, Springer.

# Model Parameterization

Carbon Model: $NPP = C_{Phyto} \times \mu$

Absorption Model: $NPP = E(\lambda) \times a_{\phi}(\lambda) \times \phi_{\mu}$

Combined Eqs: $\mu = E(\lambda) \times a_{\phi}(\lambda) \times \phi_{\mu} / C_{Phyto}$

$\left.\begin{matrix} \text{Absorption Model} \\ \text{Combined Eqs} \end{matrix}\right\}$ CAFE Model

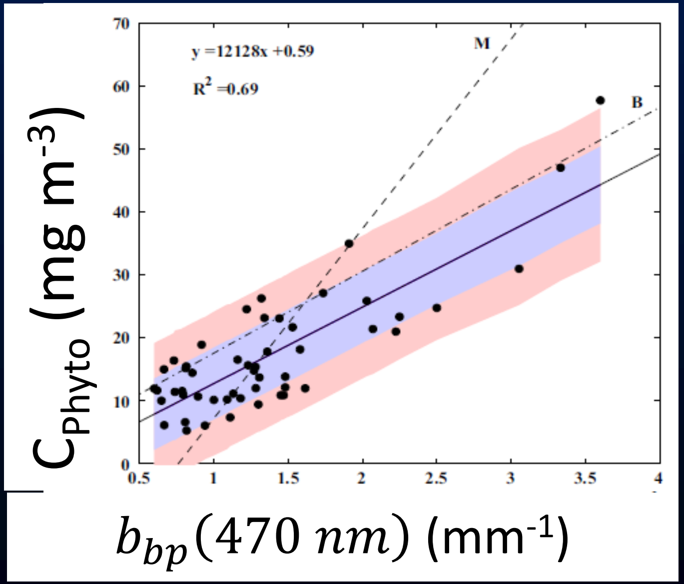
Where: $E(\lambda)$ is spectral extrapolation of PAR

$C_{Phyto}$ is derived from Graff et al. (2015)

$b_{bp}(\lambda)$ are from the GIOP-DC

$a_{\phi}(\lambda)$ is modeled as a function of Chl *a*

$\phi_{\mu}$ is the quantum efficiency of growth



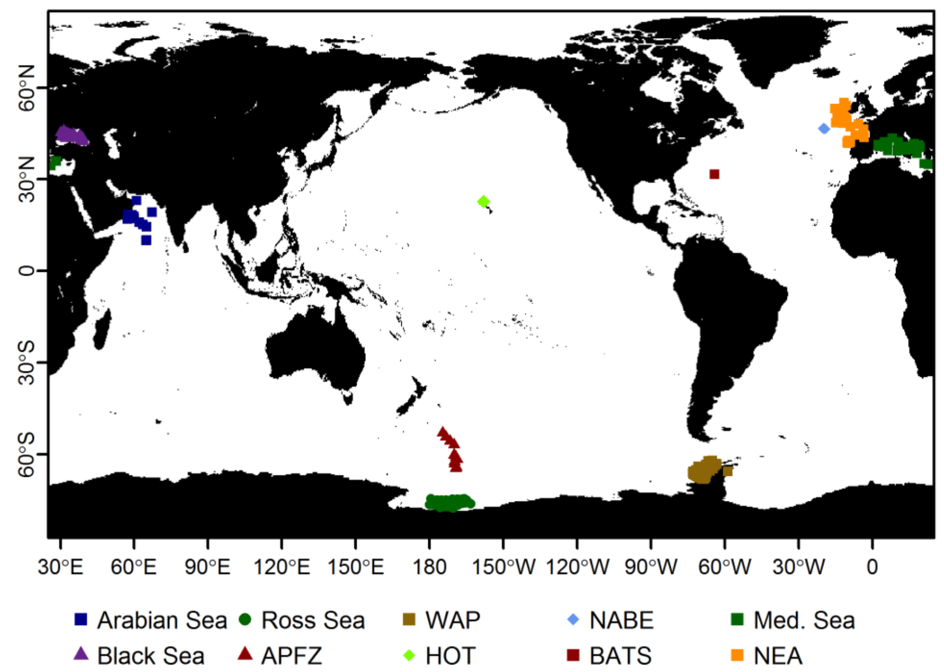

Graff, J.R. 2015. Analytical phytoplankton carbon measurements spanning diverse ecosystems. *Deep Sea Res. I.* 102: 16-25.

# Model Validation – PPARR Approach

THE CAFE Model has been evaluated against a spatially robust set of in-situ NPP measurements (Saba et al. 2011).

**An evaluation of ocean color model estimates of marine primary productivity in coastal and pelagic regions across the globe**

V. S. Saba[1,2], M. A. M. Friedrichs[1], D. Antoine[3], R. A. Armstrong[4], I. Asanuma[5], M. J. Behrenfeld[6], A. M. Ciotti[7], M. Dowell[8], N. Hoepffner[8], K. J. W. Hyde[9], J. Ishizaka[10], T. Kameda[11], J. Marra[12], F. Mélin[8], A. Morel[3], J. O'Reilly[9], M. Scardi[13], W. O. Smith Jr.[1], T. J. Smyth[14], S. Tang[15], J. Uitz[16], K. Waters[17], and T. K. Westberry[6]




$$RMSD = \left( {}^{1}/_{n} \sum_{i=1}^{n} \Delta(|\log_{10} NPP_{mod} - \log_{10} NPP_{obs}|)^2 \right)^{0.5}$$

$$Bias = mean(\log_{10} NPP_{mod}) - mean(\log_{10} NPP_{obs})$$

# Model Validation – PPARR Approach

- In the PPARR approach, direct field measurements (e.g. Chl, PAR, SST) are used to populate the various NPP models.

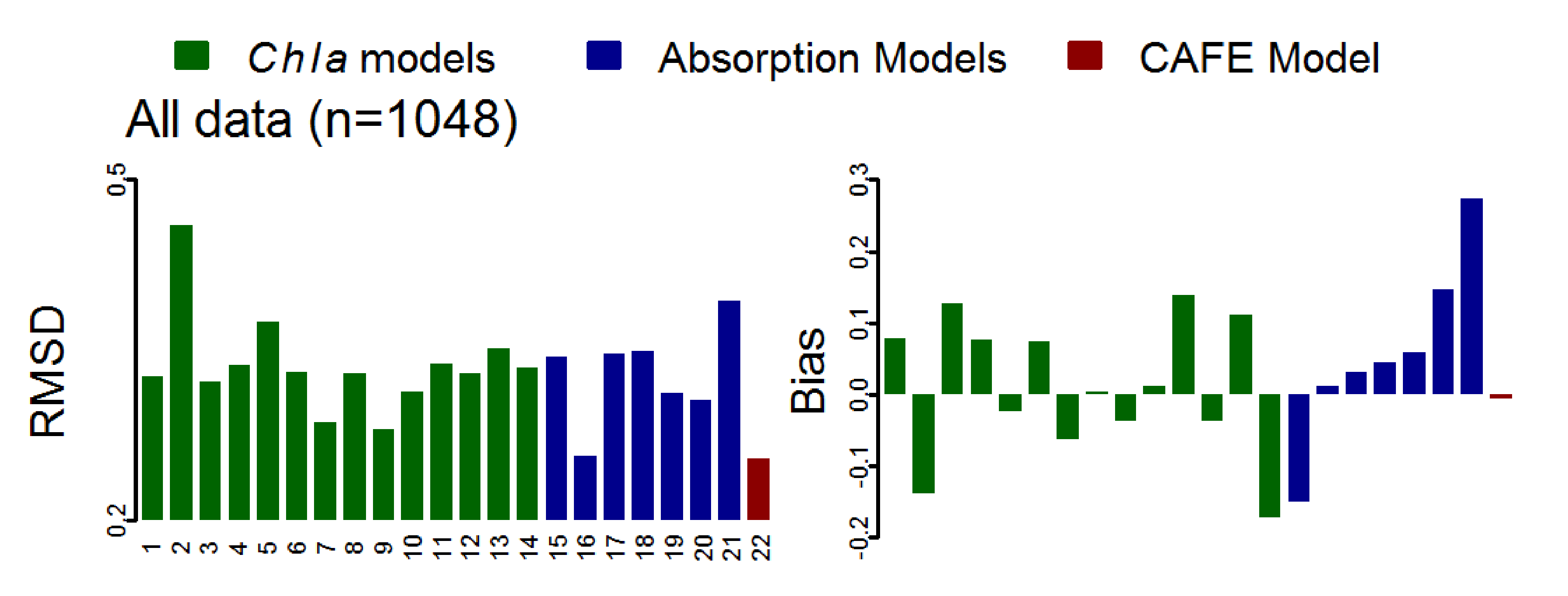
| *Metadata* | *Chl* | *PAR* | *SST* | *MLD* | *NPP* |
|---|---|---|---|---|---|
| BATS | 0.097 | 17.8 | 21.78 | 83.26 | 218.98 |
| BATS | 0.096 | 29.38 | 20.88 | 123.05 | 306.06 |
| BATS | 0.207 | 32.16 | 20.01 | 125.13 | 799.44 |

- As IOPs were not measured in the majority of models, $a_{dg}(\lambda)$, $S_{dg}(\lambda)$ and $b_{bp}(\lambda)$ were estimated from geo-located monthly climatology.

- The phytoplankton absorption coefficient ($a_{\phi}(\lambda)$) was estimated from Chl and coefficients presented in Bricaud's (1995) global dataset analysis

# Model Validation – PPARR Approach

- When compared to in-situ data, the CAFE model has higher model skill (RMSD = 0.256) and lower model bias (Bias = 0.003) than any other published NPP model.

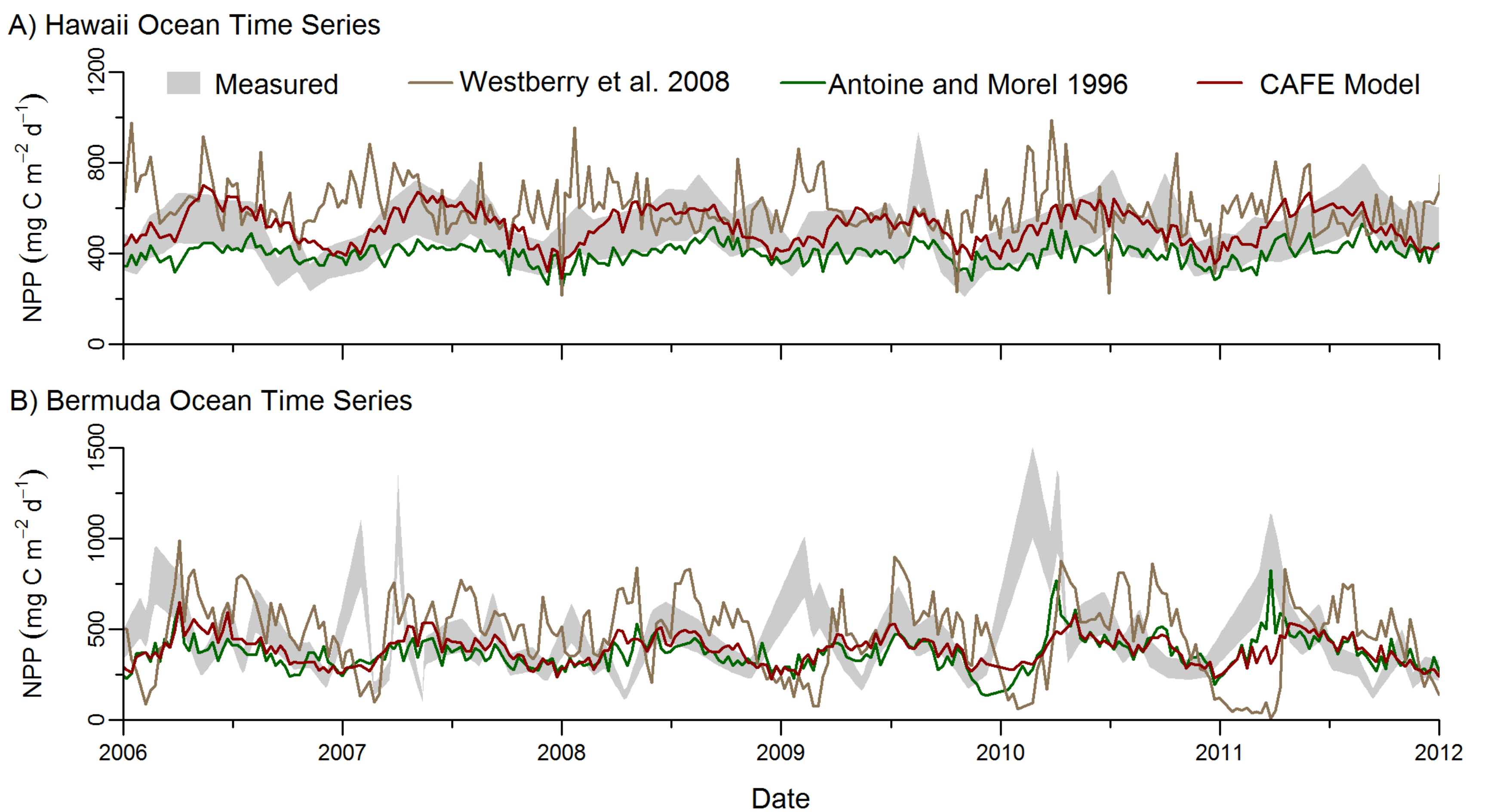



- For context, the lowest RMSD for Chl *a* retrievals is 0.259 (Brewin et al. 2015)


Brewin et al. 2015. The ocean colour climate change initiative: III: A round-robin comparison in in-water bio-optical algorithms. *Rem. Sens. Environ.* 162: 271-294.

# Model Validation – Direct Satellite Measurements

The CAFE model was also ran using direct satellite measurements across the MODIS Aqua record and compared to the HOT (RMSD = 0.11) and BATS (RMSD = 0.24) NPP time series.

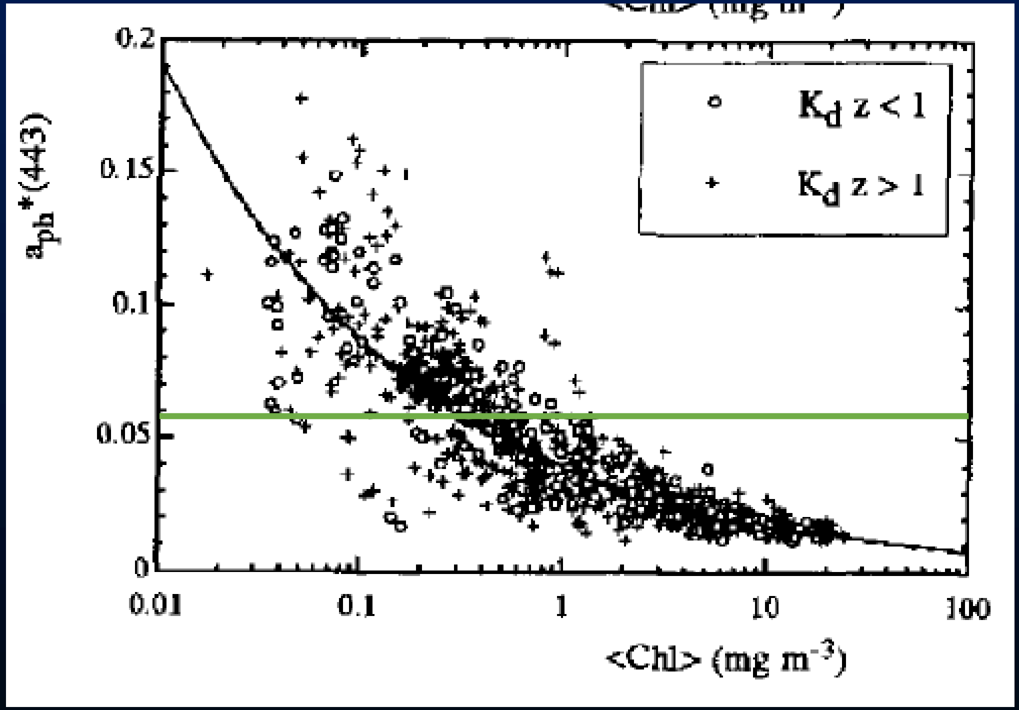


# A Comment on the GIOP-DC

- The CAFE MODEL

  $a_\phi(\lambda) = \text{Chl} \times a^*_\phi(\lambda)$ where $a^*_\phi(\lambda)$ are wavelength and Chl dependent coefficients from Bricaud (et al 1995).

The GIOP-DC follows the same principle, but $a^*_\phi$ is NOT Chl-dependent

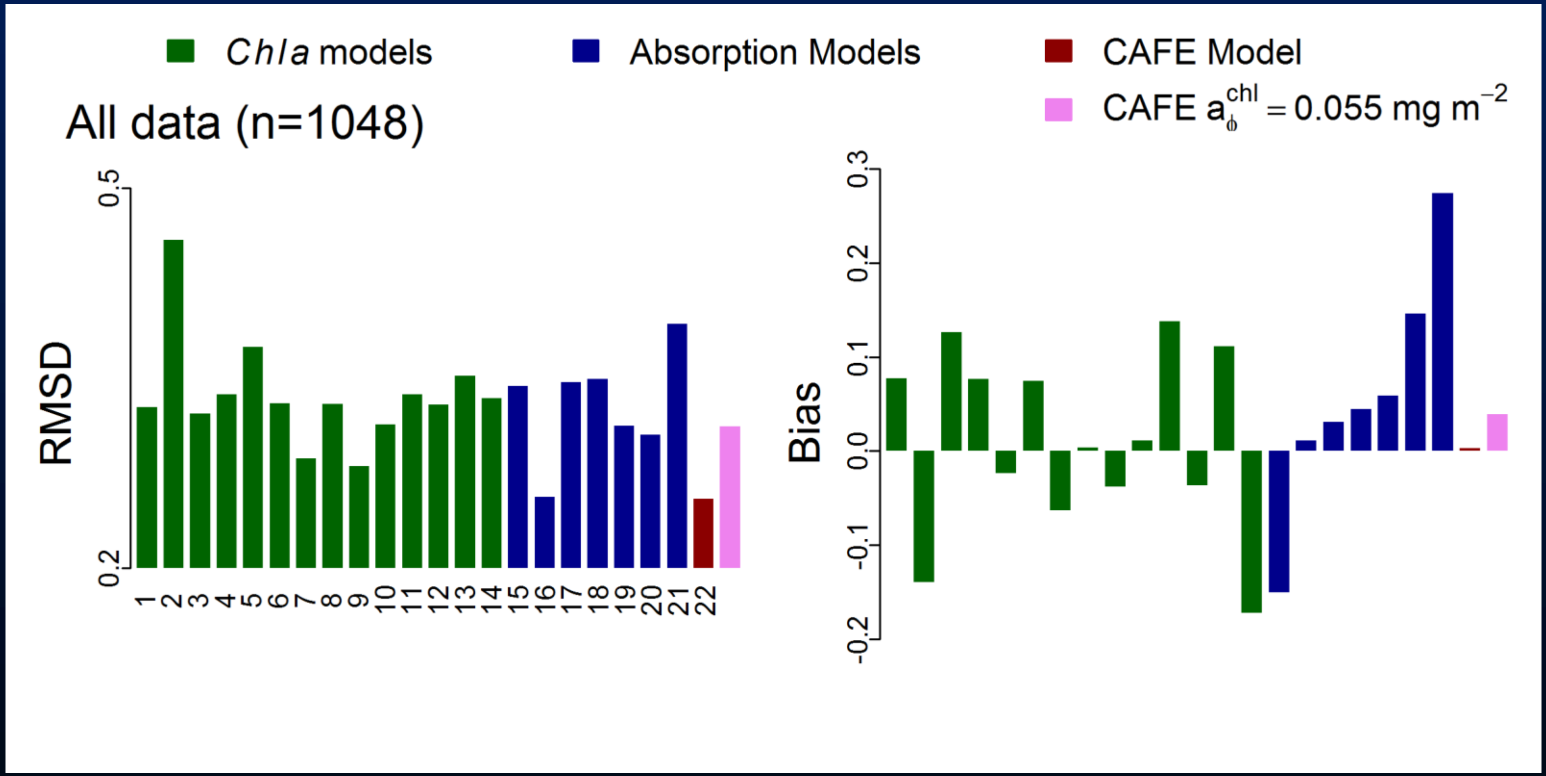



$a^*_\phi(443) = 0.055$ mg m$^{-2}$ at all [Chl] in the GIOP-DC


Bricaud et al. 1995. Variability in the chlorophyll-specific absorption coefficients of natural phytoplantkon: Analysis and parameterization. *J. Geophys. Res.* 100: 13321-13332.

# A Comment on the GIOP-DC

- Adopting the GIOP-DC approach to derive $a^*_\phi(\lambda)$ would have significantly lowered model skill and increased model bias.



# The Derivation of Absorbed Energy

## Other Absorption Models

$$\text{Absorbed Energy} = \int_0^{Zeu} E_Z\,(\lambda) \times a_\phi(\lambda)$$

- Calculation is sensitive to:
  - Spectral extrapolation of PAR
  - $a_\phi(\lambda)$
  - Downwelling attenuation coefficient
  - Estimate of upwelling irradiance
  - Demarcation of euphotic depth

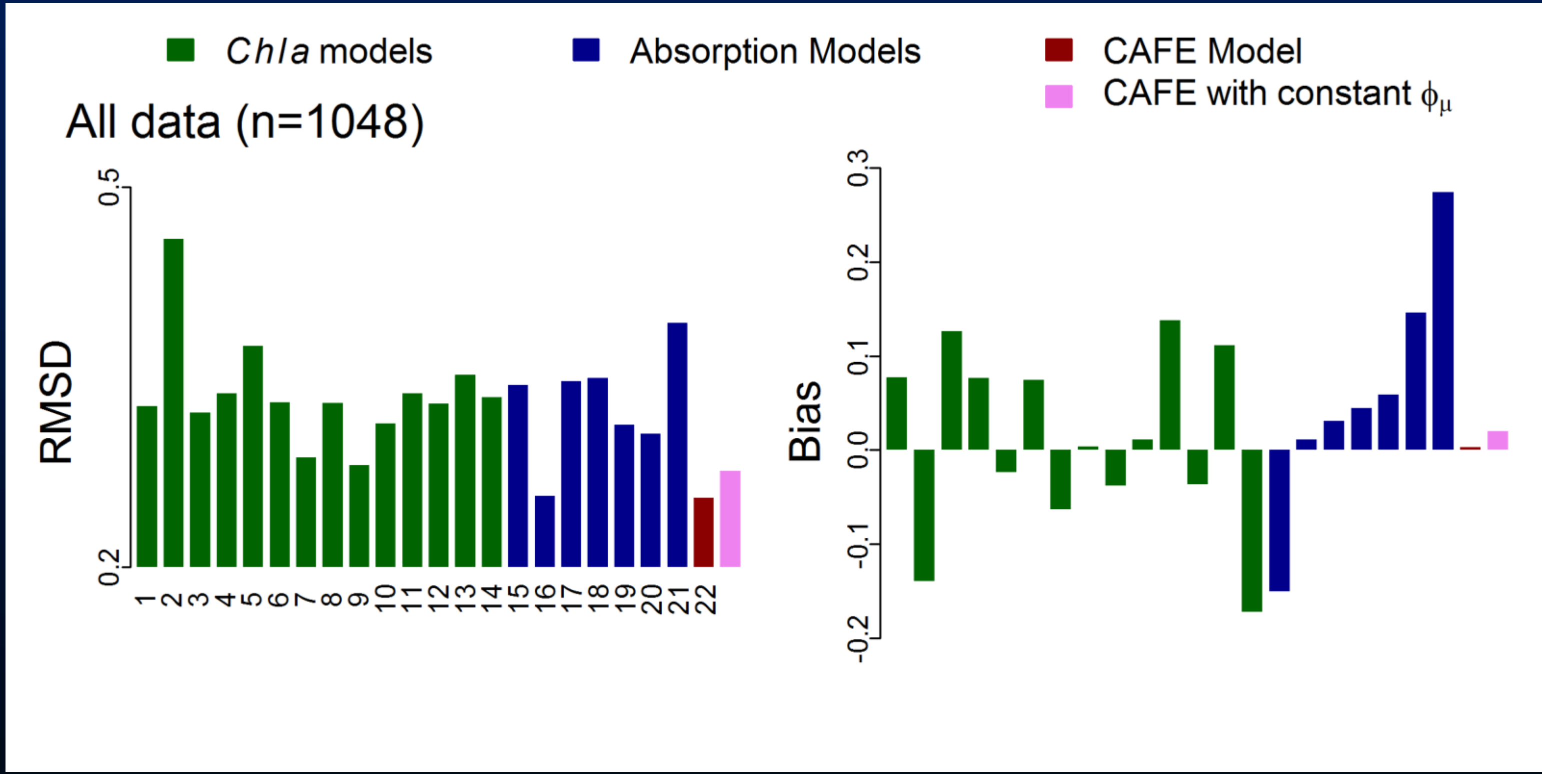
## CAFE Model

$$\text{Absorbed Energy} = E_Z(\lambda) \times a_\phi(\lambda)/a(\lambda)$$

- Calculation is sensitive to:
  - Spectral extrapolation of PAR
  - $a_\phi(\lambda)$ and $a_{dg}(\lambda)$

# A Comment on the GIOP-DC

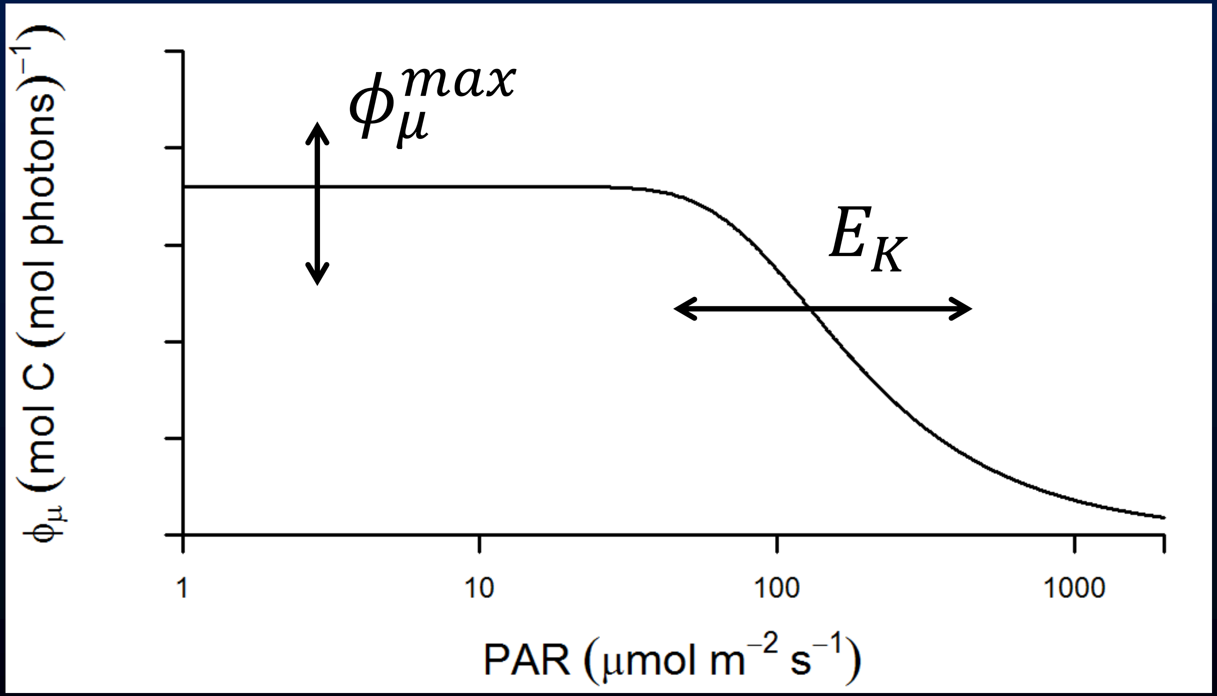
- A simplified version of the CAFE model where NPP is the product of absorbed energy and a globally constant $\phi_\mu$ (0.011 mol C mol photons$^{-1}$) has a higher model skill (RMSD = 0.27) than most other models.



# Model Parameterization

$\phi_\mu$ is modeled as modified PE curve: $\phi_\mu = \phi_\mu^{max} \times tanh(E_K/E)$

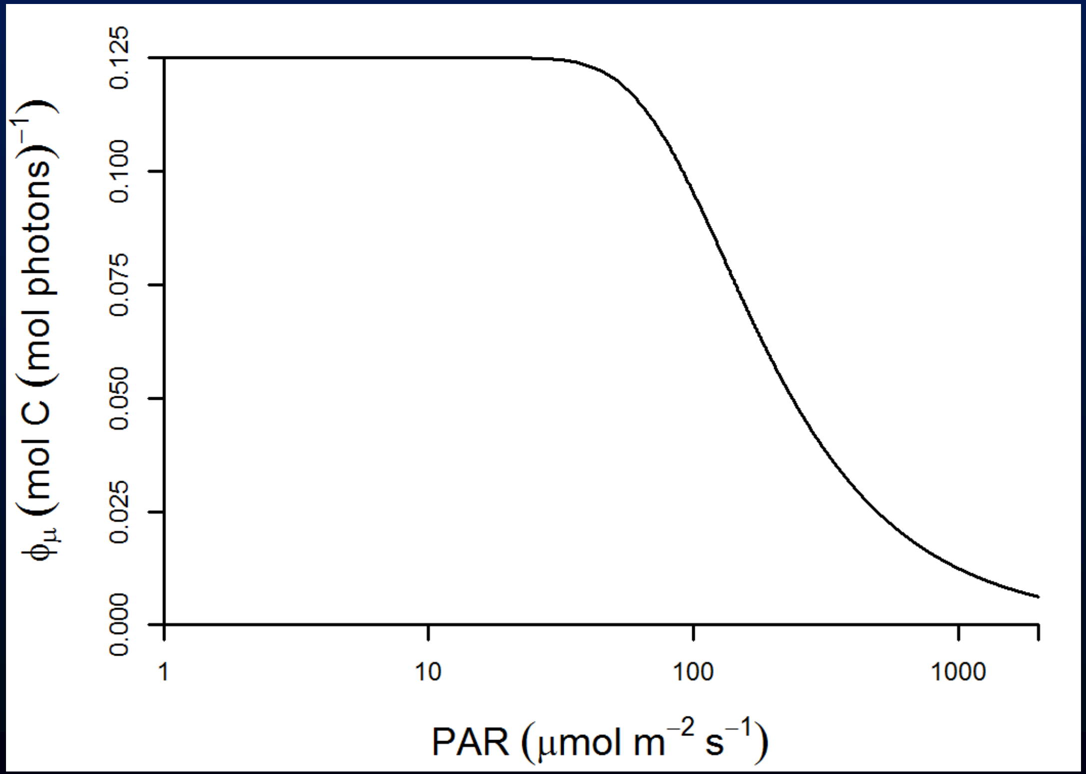
Where $E_K$ defines the fraction of absorbed energy passed to the photosynthetic reaction centers, and $\phi_\mu^{max}$ defines the conversion of absorbed *photosynthetic* energy into carbon biomass.



# Model Parameterization: $\phi_\mu^{max}$

Other absorption-based models:

- $\phi_\mu^{max}$ is globally constant: 0.060 mol C (mol photons)$^{-1}$ (Smyth et al. 2005; Marra et al. (2007)
- $\phi_\mu^{max}$ is globally variable: 0.058 ± 0.038 mol C (mol photons)$^{-1}$ (Antione and Morel 1996)



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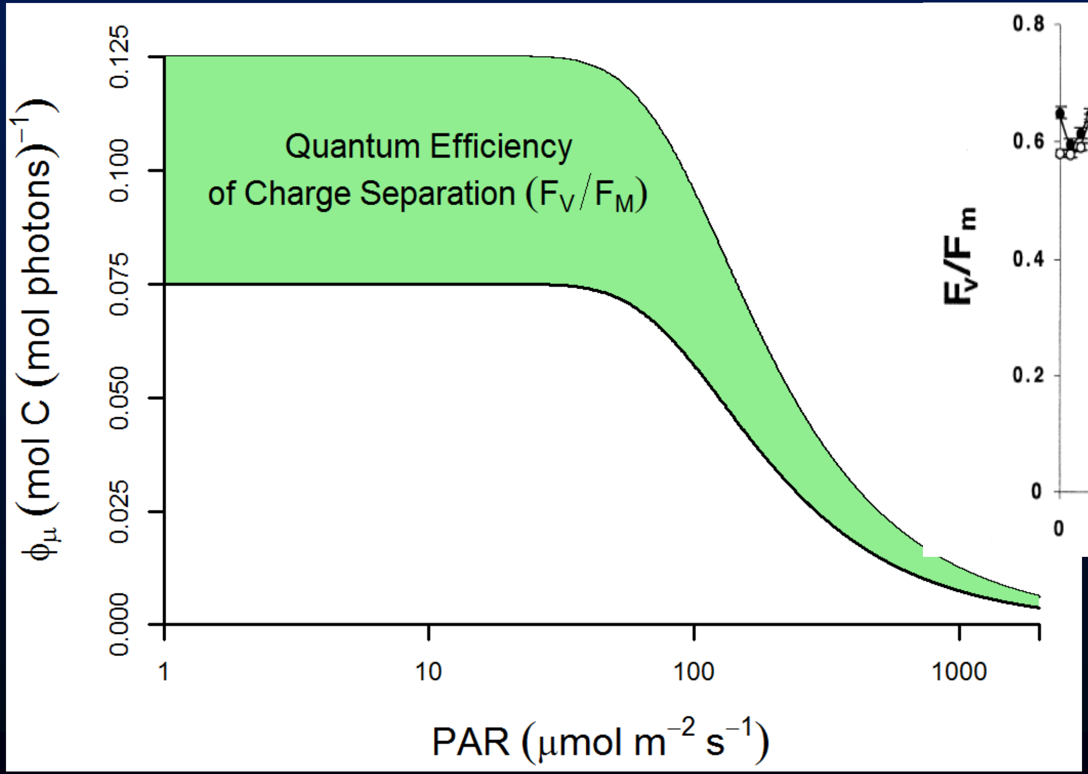


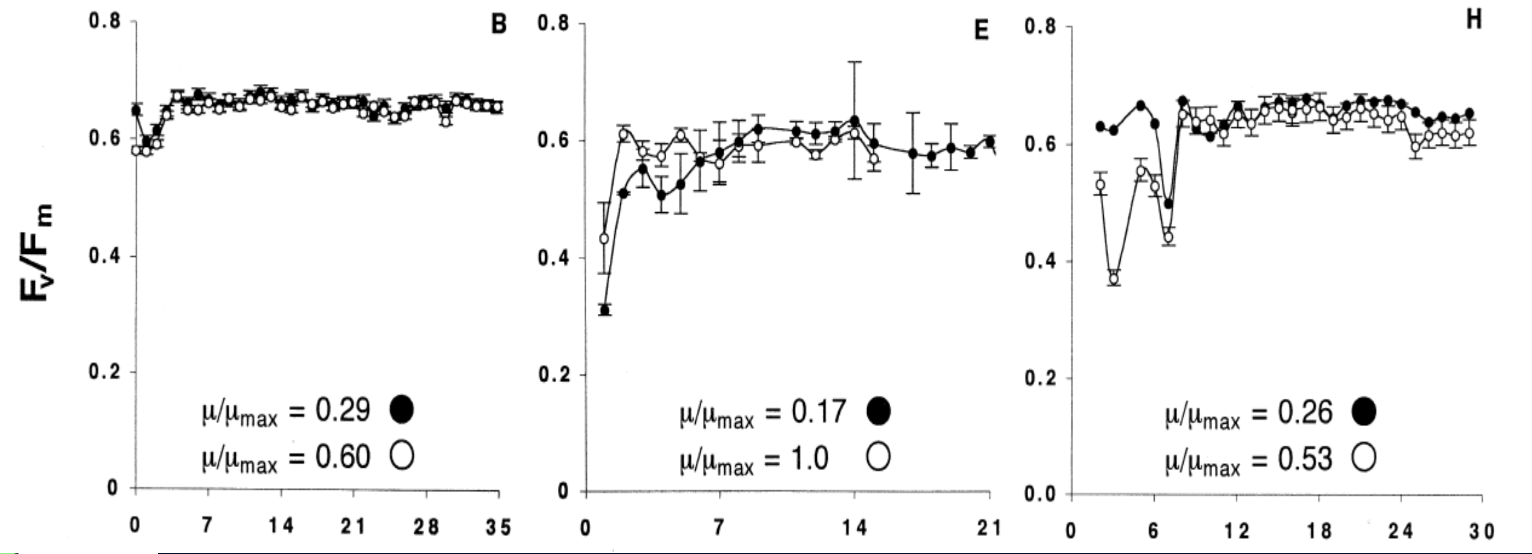


Parkhill et al. 2001. Fluorescence-based maximum quantum yield for for PSII as a diagnostic for nutrient stress. *J. Phycol.* 37:517-529.

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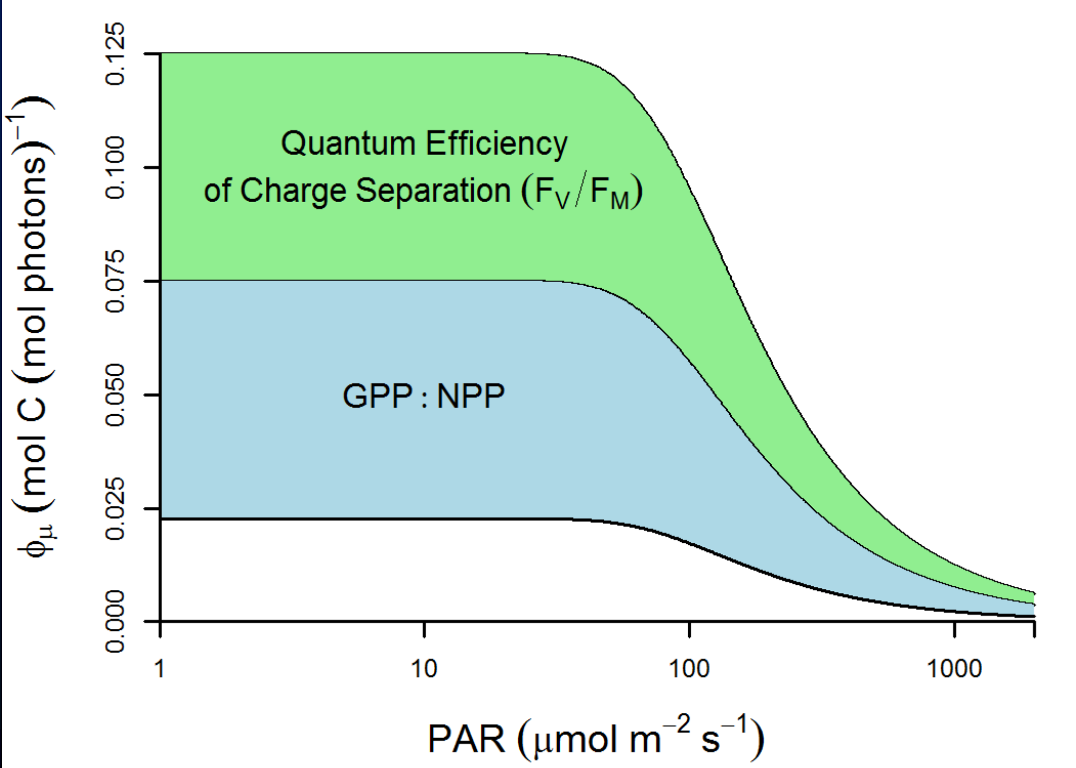


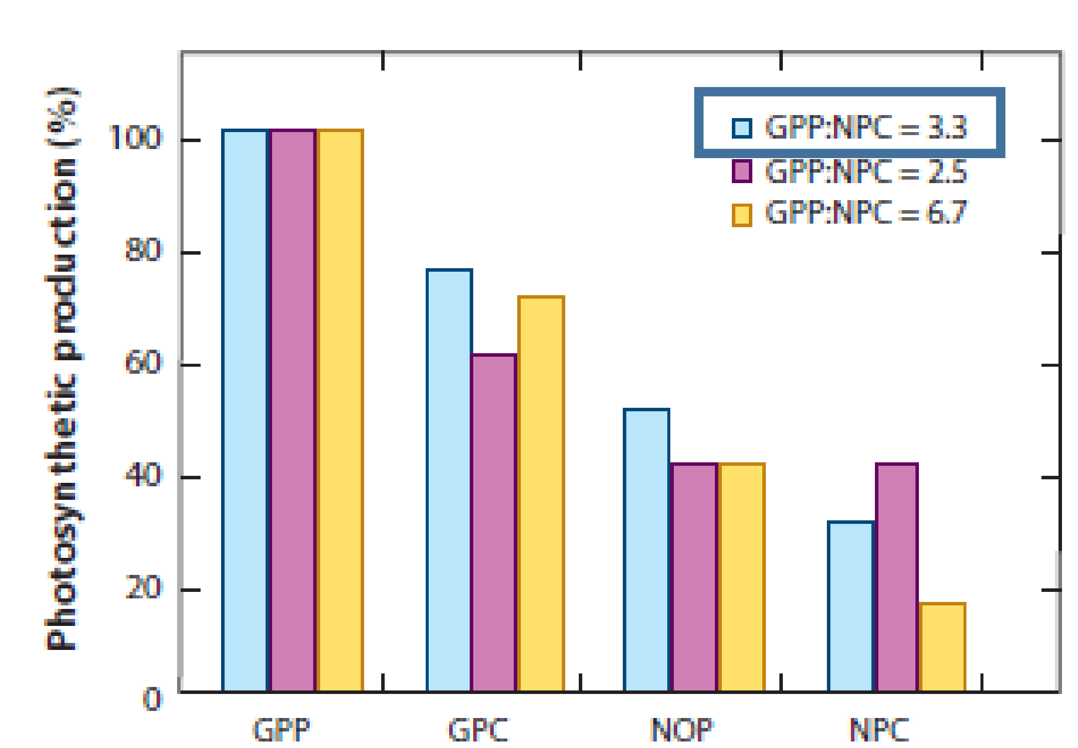


Halsey and Jones 2015. *Ann. Rev. Mar . Sci. 7:*265-280.

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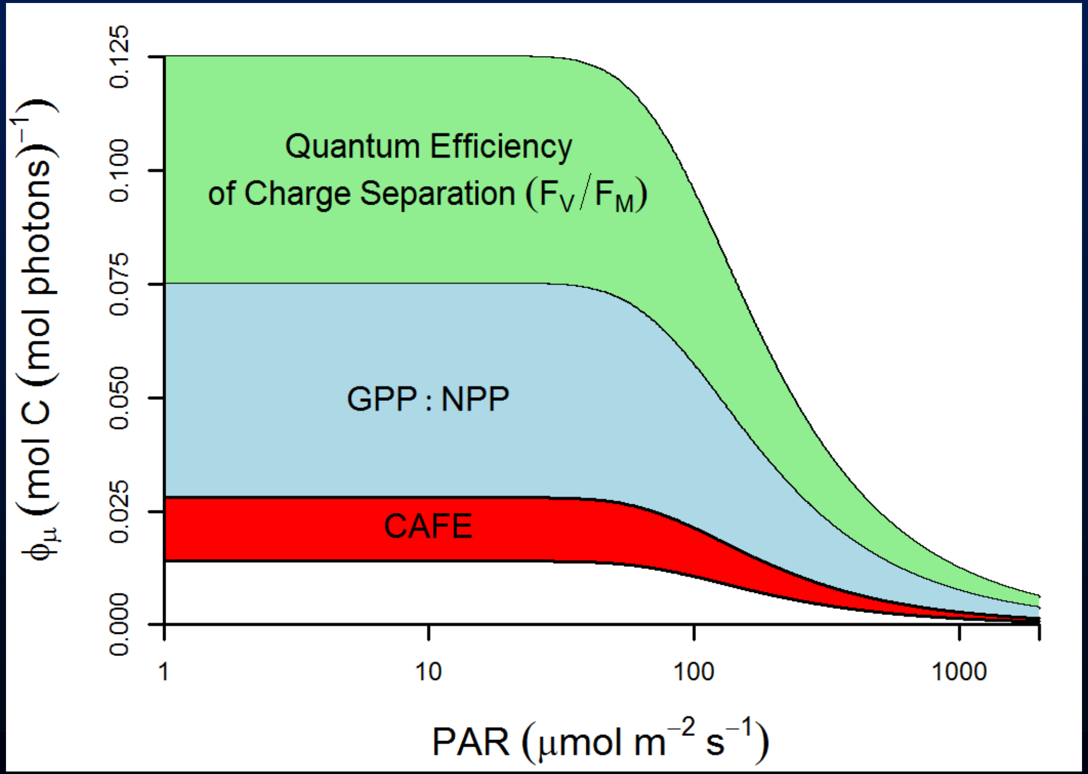


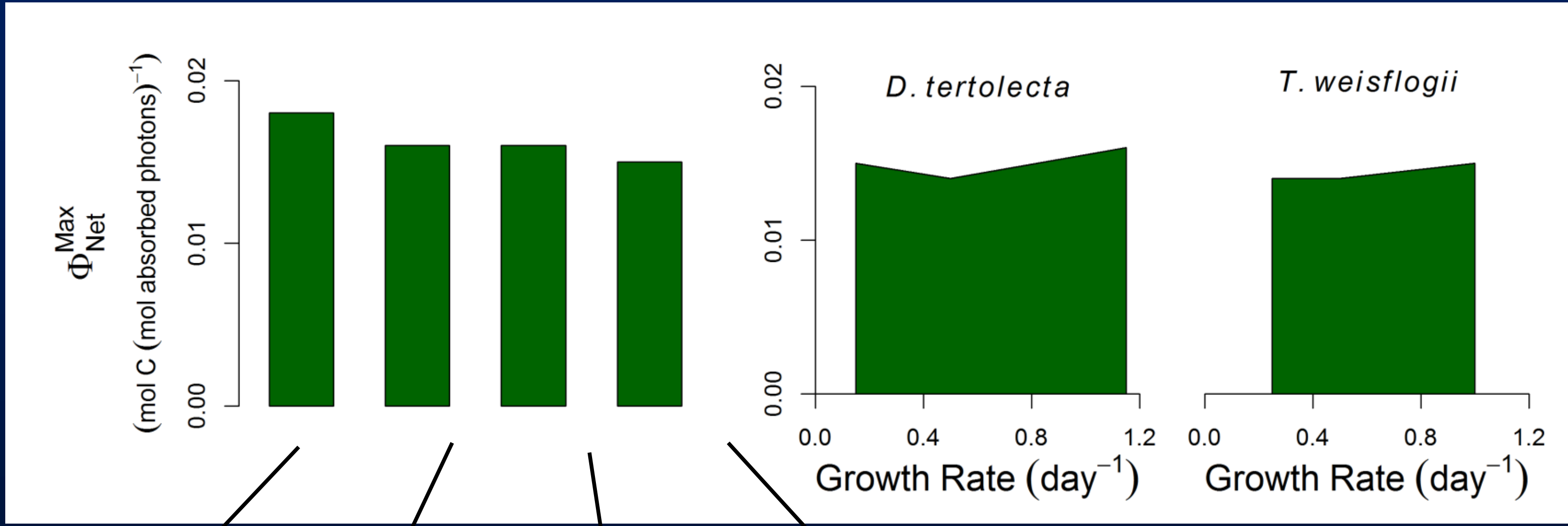

| | $E_k$ | $P^B_{max}$ | $\alpha^B$ | $\bar{a}^*$ | $\Phi_{cmax}$ |
|---|---|---|---|---|---|
| $E_k$ | 1.000 | | | | |
| $P^B_{max}$ | 0.508 | 1.000 | | | |
| $\alpha^B$ | −0.500 | 0.206 | 1.000 | | |
| $\bar{a}^*$ | 0.177 | 0.193 | | 1.000 | |
| $\Phi_{cmax}$ | −0.451 | 0.109 | 0.796 | −0.364 | 1.000 |
| [Chl *a*] | | **0.290** | | **−0.301** | **0.214** |
| $f_{micro}$ | | **0.258** | | **−0.214** | **0.106** |
| $f_{nano}$ | **−0.234** | | **0.229** | | **0.165** |
| $f_{pico}$ | **0.116** | **−0.231** | **−0.176** | **0.261** | **−0.247** |
| NPP | **0.604** | **0.138** | **−0.468** | **0.283** | **−0.486** |
| T | **0.378** | | **−0.369** | **−0.139** | **−0.150** |
| [Nut] | **−0.201** | | **0.116** | **−0.123** | **0.158** |
| $z/Z_{eu}$ | **−0.465** | **−0.320** | **0.254** | **−0.220** | **0.317** |

Uitz et al. 2008. Relating phytoplankton photophysiological properties to community structure. *Limnol. Oceanogr.* 53: 614-630

# Model Validation: $\phi_{\mu}^{max}$

Light-limited cultures

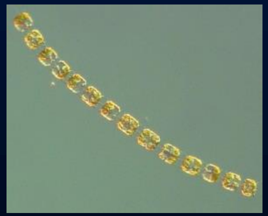
Nitrogen-limited cultures




*Micromonas pusilla*

*Dunaliella tertiolecta*

*Ostreococcus tauri*



*Thalassiosira weissflogii*

Halsey et al 2014. *Metabolites. 4:*260-280*. Also:* Laws and Bannister 1980. Marra et al. 2007.

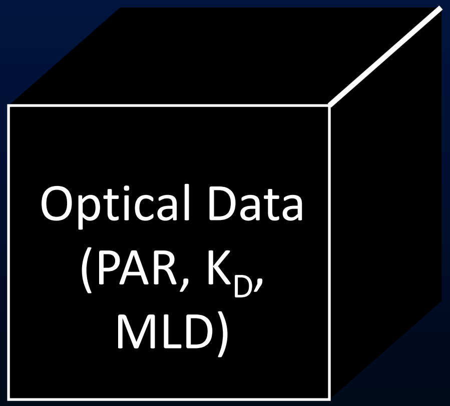
# Model Parameterization: $E_K$

Other absorption-based models:

- $E_K$ is globally constant at 116 mmol m$^{-2}$ s$^{-1}$ (Marra et al. (2007)
- $E_K$ varies with sea-surface temperature (SST) (Antione and Morel 1996; Smyth et al. 2005)

CAFE Model:

- $E_K$ varies with Growth Irradiance (Behrenfeld et al. 2015)




nature climate change
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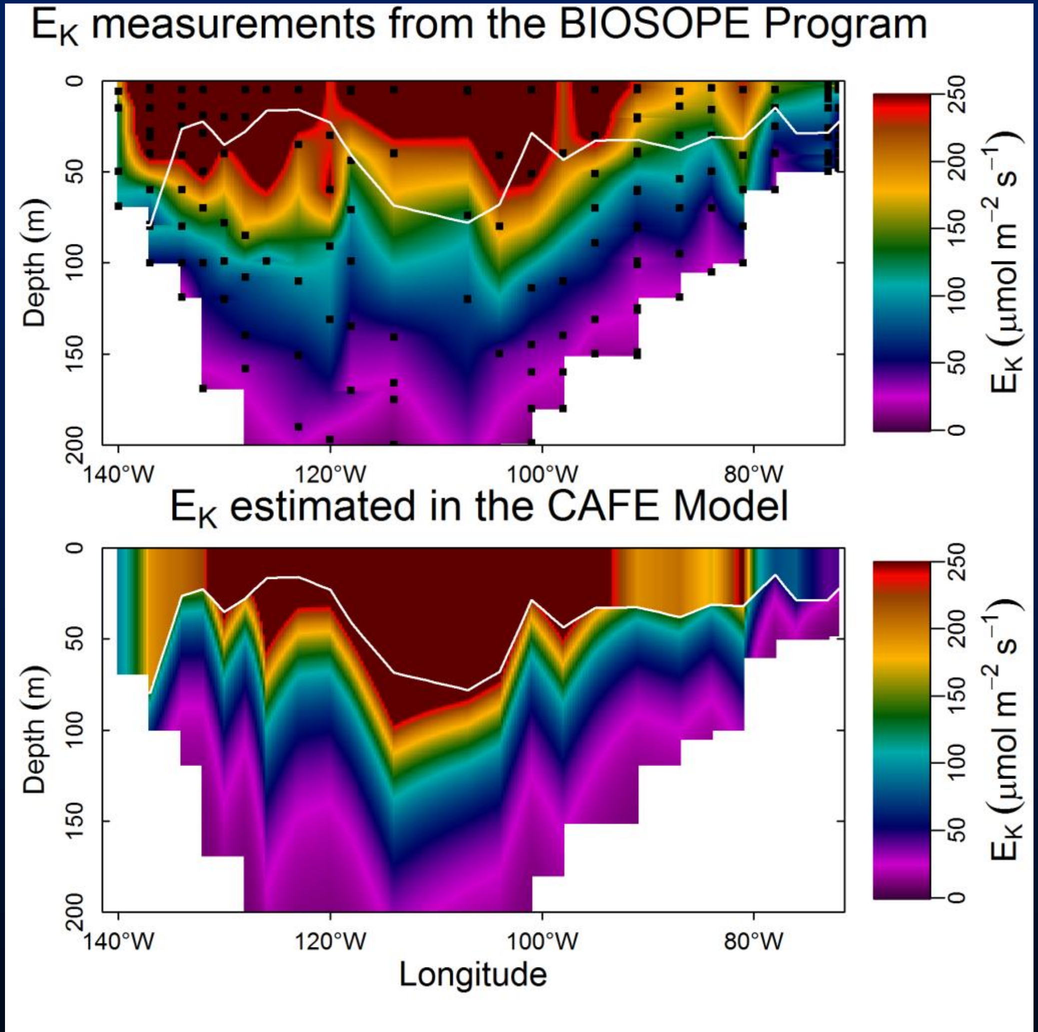
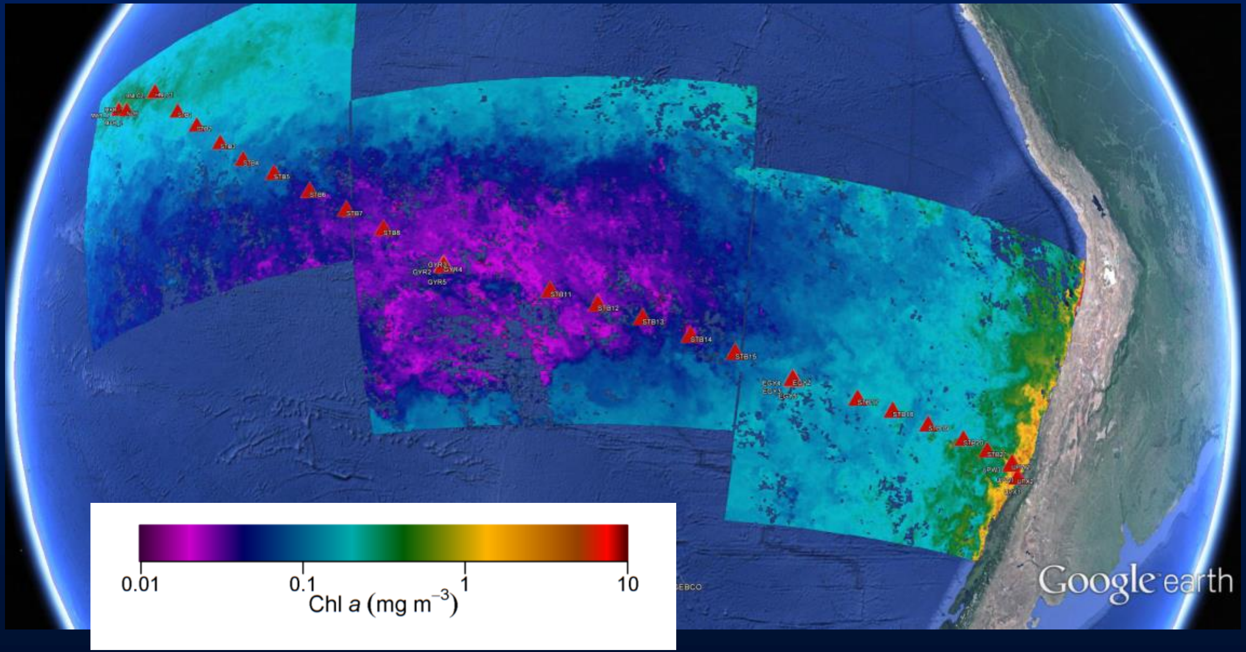
## Revaluating ocean warming impacts on global phytoplankton

Michael J. Behrenfeld[1*], Robert T. O'Malley[1], Emmanuel S. Boss[2], Toby K. Westberry[1], Jason R. Graff[1], Kimberly H. Halsey[3], Allen J. Milligan[1], David A. Siegel[4] and Matthew B. Brown[1]

# Model Validation: $E_K$

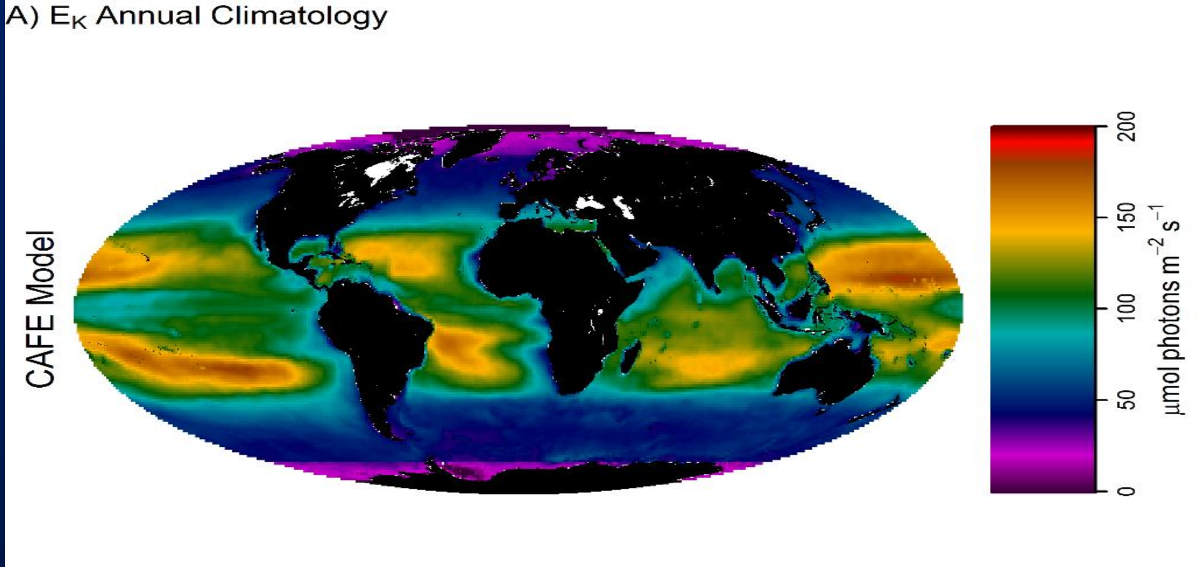


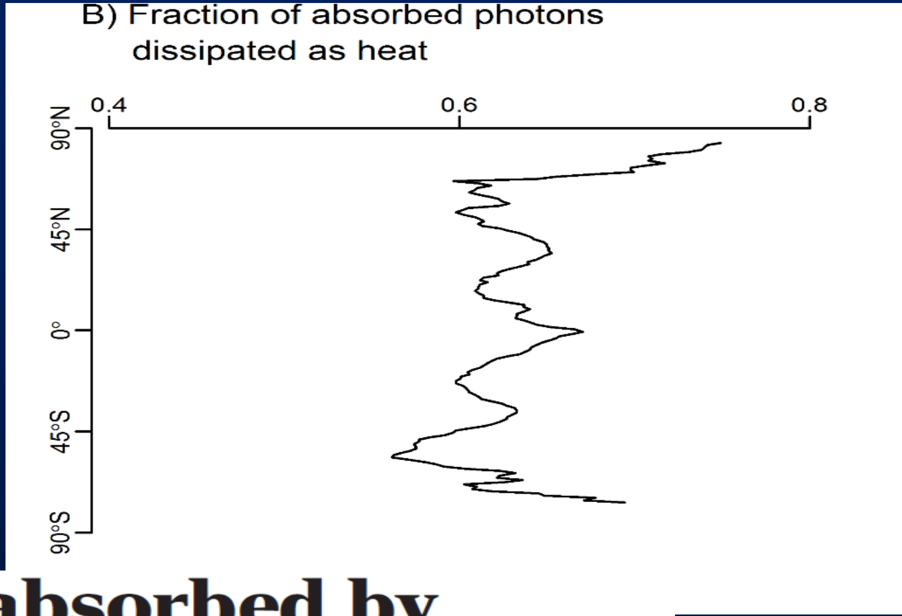




BIOSOPE stations, Nov-2004 Chl overlay

Huot et al. 2007. Relationship between photosynthetic parameters and different proxies of phytoplankton biomass in the subtropical ocean. *Biogeosciences*. **4**: 853-868.

# Model Validation: $E_K$



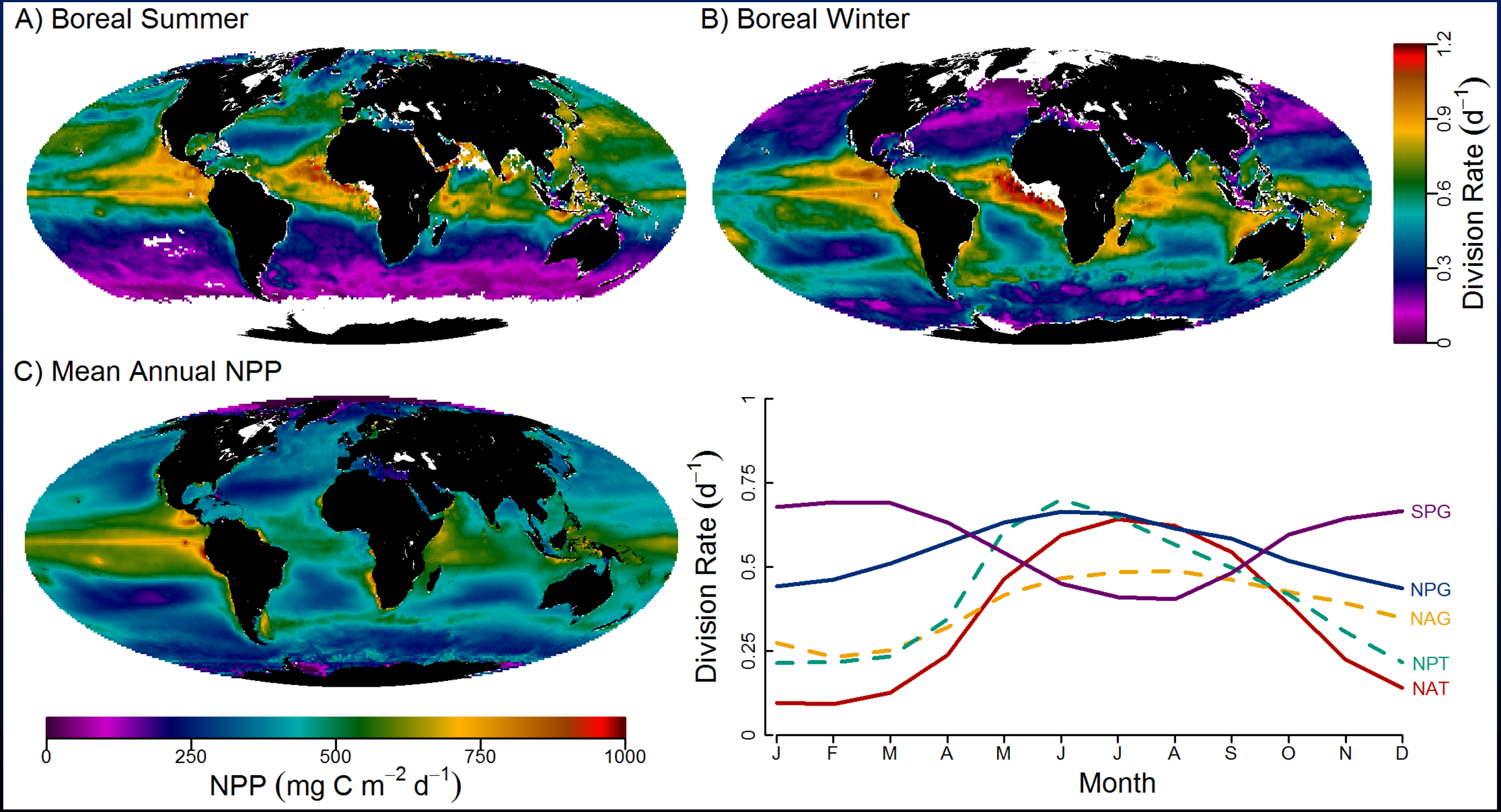

## The fate of photons absorbed by phytoplankton in the global ocean

Hanzhi Lin,[1*] Fedor I. Kuzminov,[1] Jisoo Park,[2] SangHoon Lee,[2]
Paul G. Falkowski,[1,3]† Maxim Y. Gorbunov[1]†

Solar radiation absorbed by marine phytoplankton can follow three possible paths. By simultaneously measuring the quantum yields of photochemistry and chlorophyll fluorescence in situ, we calculate that, on average, ~60% of absorbed photons are converted to heat, only 35% are directed toward photochemical water splitting, and the rest are reemitted as fluorescence. The spatial pattern of fluorescence yields and lifetimes strongly suggests that photochemical energy conversion is physiologically limited by nutrients. Comparison of in situ fluorescence lifetimes with satellite retrievals of solar-induced fluorescence yields suggests that the mean values of the latter are generally representative of the photophysiological state of phytoplankton; however, the signal-to-noise ratio is unacceptably low in extremely oligotrophic regions, which constitute 30% of the open ocean.

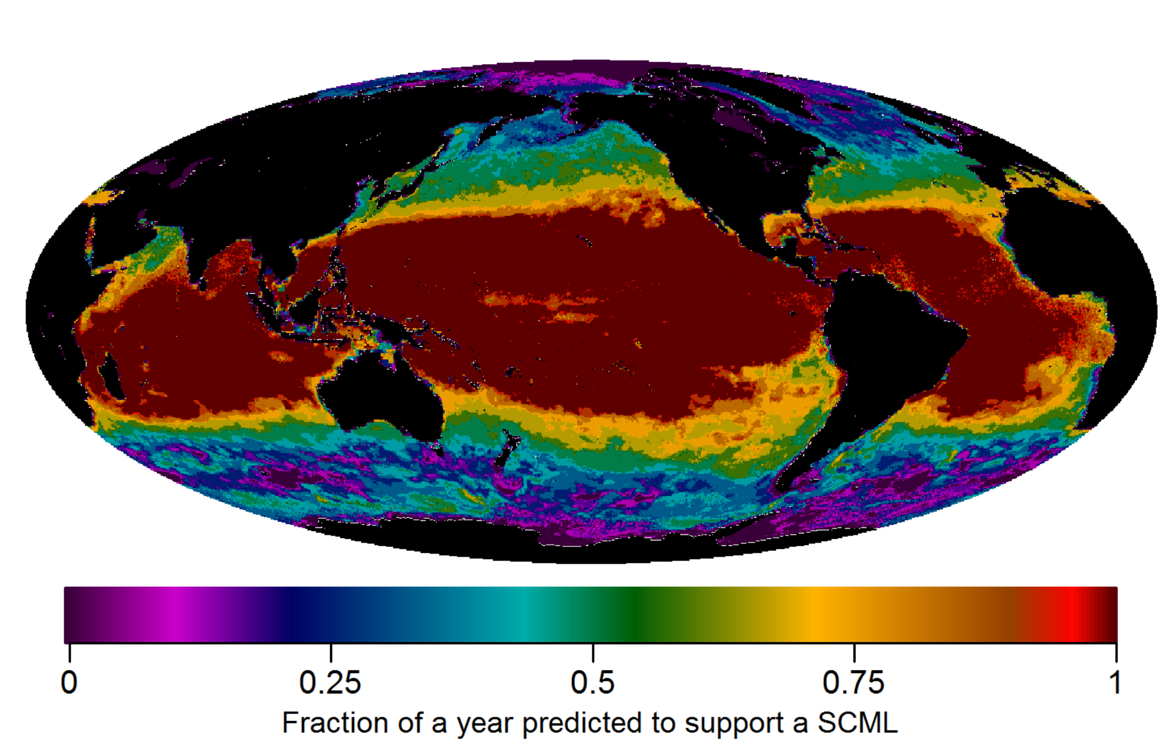
# Model Climatology

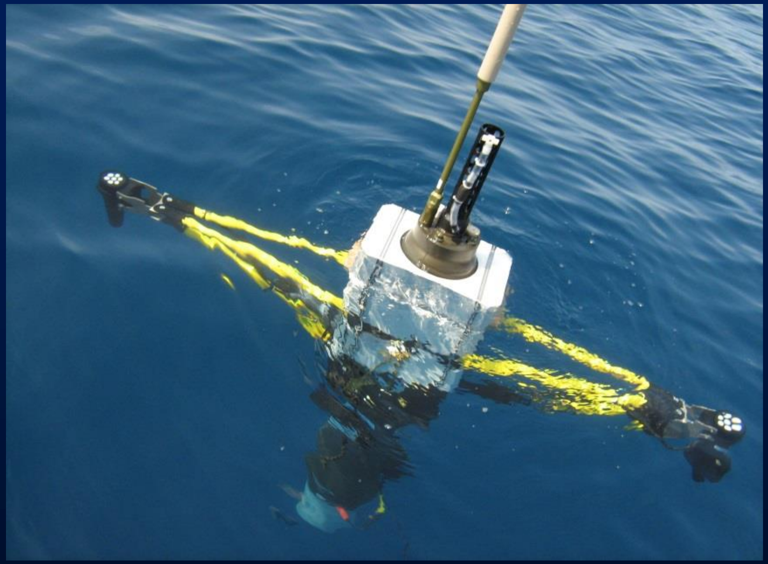
Global NPP estimated from MODIS monthly climatology is 54.8 Pg C $year^{-1}$



# Future Directions

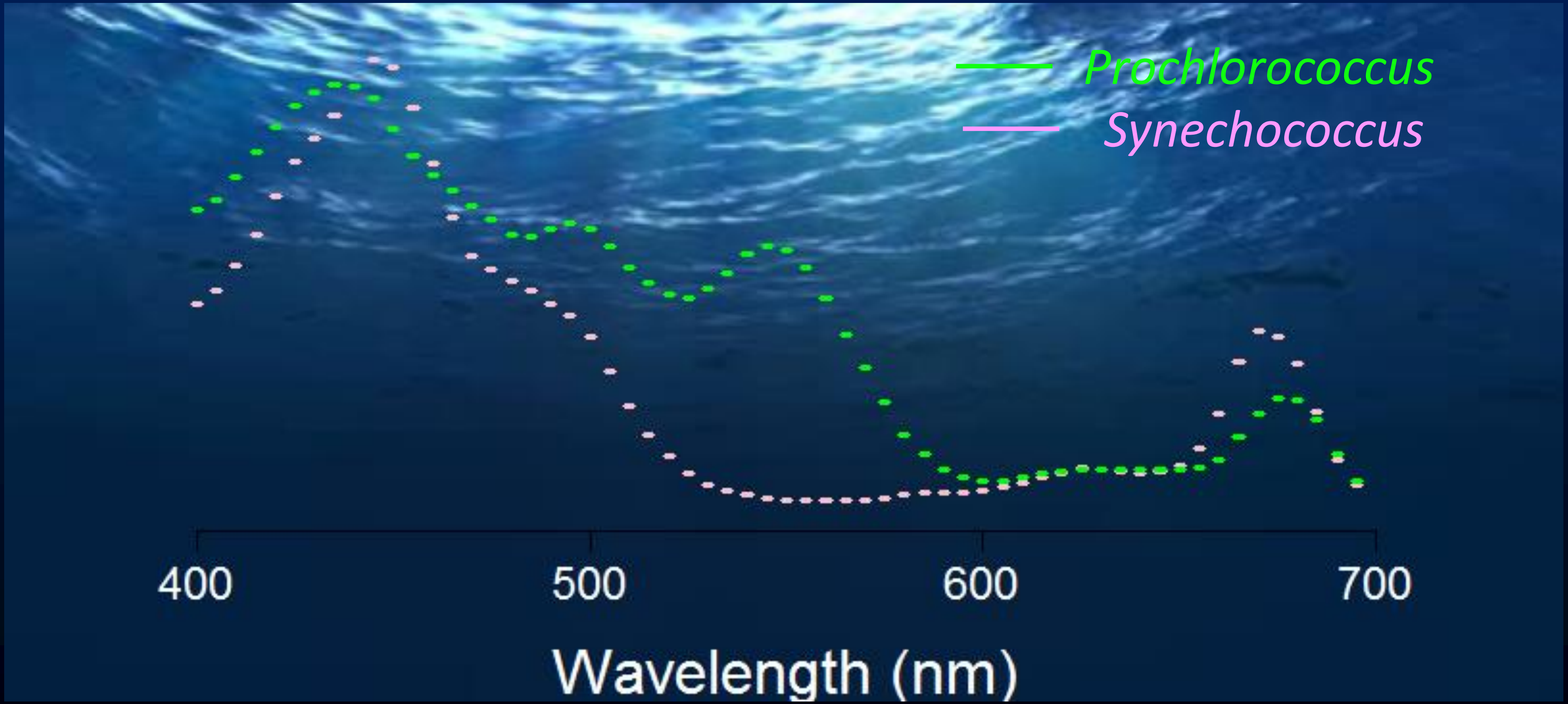
- Most phytoplankton biomass is hidden from satellite measurements of ocean color.
- BIO-Argo profiles can help fill in this missing data



# Future Directions

- Hyperspectral ocean color data (e.g. PACE) should provide improved estimation of IOPs, potentially allowing for taxonomic discrimination from space



# Questions?